Analysis of a Plasmonic Pole-Absorber Using a Periodic Structure

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SUMMARY A plasmonic black pole (PBP) consisting of a series of touching spherical metal surfaces is analyzed using the finite-difference time-domain (FDTD) method with the periodic boundary condition. First, the wavelength characteristics of the PBP are studied under the assumption that the PBP is omnidirectionally illuminated. It is found that partial truncation of each metal sphere reduces the reflectivity over a wide wavelength range. Next, we consider the case where the PBP is illuminated with a cylindrical wave from a specific direction. It is shown that an absorptivity of more than 80% is obtained over a wavelength range of $\lambda = 500$ nm to 1000 nm. Calculation regarding the Poynting vector distribution also shows that the incident wave is bent and absorbed towards the center axis of the PBP.

key words: plasmonic devices, frequency-dependent FDTD method, trapezoidal recursive convolution

1. Introduction

Considerable interest has been directed towards a broadband omnidirectional light absorber, which is often called an optical black hole. Theoretical study reveals that metamaterial structures are effective for achieving nearly 100% absorption [1]. This theoretical prediction was successfully demonstrated at microwave frequencies [2].

More recently, the numerical technique, such as the finite-difference time-domain (FDTD) method has been employed to investigate such structures [3]. Furthermore, graded index photonic crystals have been used to obtain a cylindrical optical black hole [4]. On the other hand, without the use of metamaterials, plasmonic phenomena in singular geometries have been studied, in which a suitably varying effective refractive-index distribution for gap surface plasmon modes can be generated [5], [6]. The use of touching subwavelength-sized metal spheres is effective, although the absorption occurs only for a specific polarization.

The authors have proposed a plasmonic pole-absorber using a periodic structure [7]–[9]. Since significant absorption is achieved almost in a visible wavelength range, we may call this absorber a plasmonic black pole (PBP) in contrast with the optical black hole proposed previously. In Ref. [7], the body-of-revolution (BOR) FDTD method [10], [11] has been employed to investigate the fundamental absorption characteristics. It should be noted, however, that the use of the BOR-FDTD method only provides the results for a non-realistic model, although the properties of the PBP can roughly be explained with high computational efficiency.

To practically and rigorously study the absorption characteristics, the use of the FDTD method in cylindrical coordinates is absolutely necessary together with a unidirectional illumination scheme. In this paper, we systematically present the characteristics of the PBP [9]. After reviewing the fundamental characteristics analyzed by the BOR-FDTD method, we consider a plasmonic pole-absorber illuminated from a specific direction. It is found that an absorptivity of more than 80% is obtained over a wavelength range of $\lambda = 500$ nm to 1000 nm. Calculation regarding the Poynting vector distribution also shows that the incident wave is bent and absorbed towards the center axis of the PBP.

2. Configuration

Figure 1 depicts the configuration of the PBP, which is assumed to be placed in free space. The PBP is basically composed of a series of touching spherical metal surfaces. Various metals can be selected to form the surfaces. In this paper, we choose aluminum since relatively large attenuation is expected in comparison with gold and silver [12]. The dispersion property is expressed as the Drude-Lorentz model [13]. Taking into account the periodicity along the $z$-axis, we only deal with a unit cell whose length is $\Lambda = 2r_z$, as shown in Fig. 1 (b) (Half the cross-sectional configura-
tion is illustrated due to the circular symmetry). The size and shape of the unit cell are controlled by the parameters \( r, r, \rho \) and \( \theta_r \), where \( r \) and \( r, \rho \) are the radii of the original and truncated spheres and \( \theta_r \) is the angle truncating the sphere. Note that a complete series of touching spheres is generated for \( \theta_r = 90^\circ \).

3. Omnidirectionally Illuminated Case

In this Section, we investigate the fundamental characteristics of the PBP with \( r, \rho = 500 \) nm. For this, we consider the case where the PBP is omnidirectionally illuminated by a vertically polarized uniform wave from the \( \rho \) direction. Although this illumination is non-realistic, this choice allows us to use the BOR-FDTD method, which has much higher computational efficiency than the conventional FDTD method with cylindrical co-ordinates. Since the one-way wave excitation is adopted, the reflection wave can readily be evaluated near the computational window edge.

For the BOR-FDTD method based on Yee’s mesh, the partial derivative with respect to \( \phi \) can be performed analytically, so that the original three-dimensional \((\rho, \phi, z)\) model is reduced to an equivalent two-dimensional \((\rho, z)\) one. This greatly contributes to reduction in the computational time and memory. The calculation parameters are chosen to be \( \Delta \rho = \Delta z = 1 \) nm. The periodic boundary condition is set in the \( \pm z \) directions. In the \( \rho \) direction, the boundary condition based on the convolutional perfectly matched layer (CPML) is placed to absorb outgoing waves towards the computational edge [14]. To take into account the metal dispersion, we employ the trapezoidal recursive convolution technique [15].

Since the PBP forms a periodic structure, higher-order diffracted waves may be generated. The diffraction wave is governed by the well-known grating equation:

\[
|k_d| = |k_0| \cos \theta_{\text{inc}} + m \frac{2\pi}{\Lambda}
\]

where \( k_0 \) is the free-space wavenumber, \( \theta_{\text{inc}} \) the angle of incidence, and \( m \) the diffraction order. \( \theta_{\text{inc}} = 90^\circ \) corresponds to the normal incidence case towards the PBP.

Figure 2 shows the reflectivity for \( \theta_{\text{inc}} = 90^\circ \) as a function of wavelength \( \lambda \). The results are presented for several values of \( \theta_r \). A Gaussian pulse wave is launched from the incidence plane. The frequency characteristics of the reflection are evaluated using the time-domain response in the observation plane. The reflectivity is evaluated, taking both zeroth- and first-order diffraction components into account. Note that no reflection occurs provided the PBP completely absorbs the incident wave. It is seen that the appreciable reflection is observed for \( \theta_r = 90^\circ \). However, the reflection is much reduced for \( \theta_r = 60^\circ \). Some fluctuated reflection observed for \( \theta_r = 60^\circ \) around 500 nm is partly due to the effects of the high-order diffraction. The first-order diffraction component appears at a wavelength of less than 578 nm, which is determined by Eq. (1). Since we fix \( r, \rho \) in this Section, \( r_z \) reduces as \( \theta_r \) is decreased. Calculation also shows that the reflectivity is more suppressed when \( \theta_r \) is taken to be 30°, corresponding to \( r_z = 134 \) nm. Similar behavior is also observed for \( \theta_r = 10^\circ \).

Figures 3 (a) and (b), respectively, illustrate the power density distributions for \( \theta_r = 90^\circ \) and 60° at \( \lambda = 655 \) nm. The field is incident at \( \rho = 600 \) nm towards the center axis. Therefore, the region of \( \rho > 600 \) nm corresponds to the reflected field region. The difference between Figs. 3 (a) and (b) observed in the region of \( \rho > 600 \) nm is due to whether the reflected wave is generated or not. Figure 3 (a)
also shows the field interference in the reflected field region, suggesting the existence of the high-order diffraction (The first-order diffraction is suppressed at \( \lambda > 1000 \text{ nm} \)). It is interesting to note that the power is highly localized at the contact point of the metal surfaces on the center axis. This corresponds to the so-called “hot site” described in Ref. [16].

For reference, the power density distribution for the horizontally polarized incident wave is illustrated in Fig. 3 (c). As expected, most of the incident wave is reflected towards \( r\phi \) direction. In other words, the present PBP acts as an efficient absorber only for the vertically polarized wave.

The time-domain analysis further shows that the power accumulates due to the drastic reduction of group velocity and effective wavelength that the surface waves experience, as the surface waves approach the contact point of the metal surfaces. Therefore, the field behavior near the contact point may be explained using the quasi-static approximation.

Final consideration in this Section is devoted to the behavior when the PBP is illuminated obliquely. Figure 4 shows the reflectivity for several angles of incidence as a function of wavelength. Again note that the normal incidence corresponds to \( \theta_{\text{inc}} = 90^\circ \). The configuration parameters are typically chosen to be \( r_p = 500 \text{ nm} \) and \( \theta_i = 30^\circ \). It is observed that the reflectivity is insensitive to \( \theta_{\text{inc}} \). This is partly due to the fact that no higher-order diffraction occurs even for \( \theta_{\text{inc}} = 70^\circ \). It can be said that the absorption properties are retained, even for the oblique incidence case.

4. Unidirectionally Illuminated Case

So far, the PBP has been studied using the BOR-FDTD method. Although the BOR-FDTD method efficiently offers the fundamental characteristics, it cannot provide the absorptivity and transmissivity because of the omnidirectional illumination. We have only inferred the absorptivity by confirming the reduction in reflectivity. To overcome this difficulty, in this Section we employ the three-dimensional FDTD method in cylindrical co-ordinates. This enables us to evaluate the absorptivity using the unidirectional illumination scheme.

The numerical parameters are taken to be the same as those used in Sect. 3, i.e., \( \Delta \rho = \Delta z = 1 \text{ nm} \). \( \Delta \phi \) is chosen to be 15°. For convenience, the incidence surface is taken to be in a range of 300° to 60°, as shown in Fig. 5. The cylindrical wave with normal incidence is illuminated towards the central axis (\( \rho = 0 \)) at \( \rho = 100 \text{ nm} \) using the one-way excitation scheme. Although we have some freedom in selecting the range of the incidence surface, the reflectivity and transmissivity should be observed taking the range of the incidence surface into account. As a result, the reflectivity is evaluated on the surface of 300° to 60° (0±60°), and the transmissivity on the surface of 60° to 300° (180 ± 120°).

Figures 6 (a) and (b), respectively, show the wavelength responses of the absorptivity for \( r_p = 500 \) and 700 nm. The results for several values of \( \theta_i \) are plotted. It is found that high absorptivity is obtained as \( \theta_i \) is decreased. The results for \( r_p = 500 \text{ nm} \) are consistent with those observed in Fig. 2. Similar tendency regarding the absorptivity is also observed for \( r_p = 700 \text{ nm} \). The spatial transition from the free space to the PBP becomes smooth, as \( r_p \) is increased. Therefore, the absorptivity property for \( r_p = 700 \text{ nm} \) is slightly better than that for \( r_p = 500 \text{ nm} \).

The reflectivity and transmissivity for \( r_p = 700 \text{ nm} \) are shown in Figs. 7 and 8, respectively. The reflectivity tends to increase as \( \theta_i \) is increased, while the transmissivity remains relatively unchanged, which is less than 0.3 regardless of the change in wavelength. Comparison with Fig. 6 (b) reveals that the deterioration of the absorptivity is mainly caused by the increase in the reflectivity. In other words, the smooth spatial transition from the free space to the PBP is absolutely necessary to achieve high absorptivity.

The necessity of the smooth transition can also be understood in the power density distributions shown in Figs. 9 (a) and (b). The two cases for \( \theta_i = 90^\circ \) and 30° are shown in the \( \rho - z \) plane. A wavelength of \( \lambda = 700 \text{ nm} \) is typically chosen. Note that the distribution is presented not only in the reflected field region but also the transmitted field region in contrast with Fig. 3.

Figures 9 (a) and (b) clearly show that the field is significantly localized around the center region, and the transmitted wave is successfully suppressed. We should recall that the surface plasmon is generated when the electric field is normal to the metallic interface. Therefore, \( \theta_i \) should be small, allowing the smooth generation of the surface plas-
mon wave. This fact is clearly seen in Fig. 9 (b). In contrast, for $\theta_r = 90^\circ$ in Fig. 9 (a), the appreciable reflection occurs, generating the interference caused by the high-order diffraction.

The power distribution for $\theta_r = 30^\circ$ is shown in Fig. 10. The distribution at $\lambda = 750$ nm is presented in the $\rho - \phi$ plane, corresponding to #1 marked in Fig. 1. For comparison, the data for free space (without the PBP) is also presented in Fig. 10 (b). Owing to the existence of the PBP, the field converges to the center axis, resulting in the significant absorption. Figure 10 (a) also demonstrates that the transmitted wave is sufficiently suppressed.

The corresponding Poynting vector distributions are, respectively, plotted in Figs. 11 (a) and (b). The vector is expressed with a 30dB scale. It should be noted that the Poynting vector for the PBP bends towards the center axis, since the field is trapped around the center axis. In contrast, the Poynting vector in free space extends as the field propagates (Since the cylindrical wave is employed for incidence,
the propagating field initially tends to focus towards the center axis, as also seen in Fig. 10 (b)).

Before concluding our research, we add some comments on the numerical accuracy of the present calculation. Needless to say, the accuracy depends on the spatial increments of the grid. Although the accuracy can be improved with smaller increments, they often require large computational resources. Fortunately, the use of the BOR-FDTD method circumvents the finite difference calculation around the $\phi$ direction with a high computational efficiency. We, therefore, employ $\Delta \rho = \Delta z = 1$ nm and $\Delta \phi = 15^\circ$ after checking the results in the BOR-FDTD method. More importantly, recent works reveal that there exist limitations of Drude-Lorentz model in the case where metallic objects are arranged in close proximity to each other, i.e., so-called nonlocal effects [17], [18]. Inclusion of the nonlocal effects is yet to be researched.

5. Conclusions

A plasmonic pole-absorber consisting of a periodic structure, so-called plasmonic black pole (PBP), has been proposed and the characteristics have been numerically investigated using the FDTD method. First, the BOR-FDTD method is employed to show the fundamental properties of the PBP for the omnidirectionally illuminated case. Appreciable reduction in reflectivity has been confirmed, which encourages us to examine a more realistic model using the unidirectional illumination scheme. Detailed analysis reveals that an absorptivity of more than 80% is obtained over a wavelength range of $\lambda = 500$ nm to $1000$ nm. Calculation regarding the Poynting vector distribution also shows that the incident wave is bent and absorbed towards the center axis of the PBP. Optimization of the configuration of the unit cell will be left for future research.

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References


